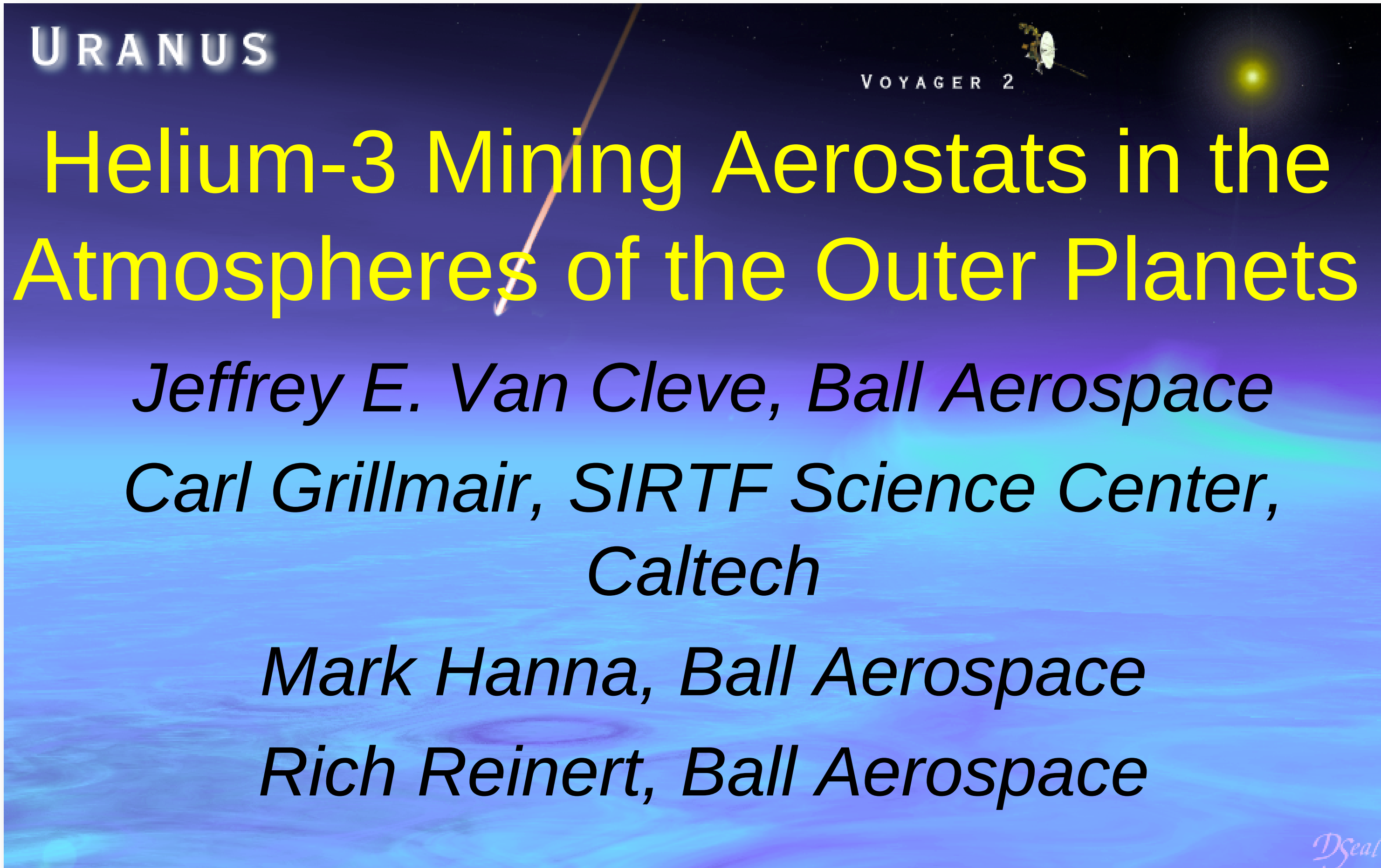

Helium-3 Mining Aerostats in the Atmospheres of the Outer Planets

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Reference: Van Cleve et. al. “Helium-3 Mining Aerostats in the Atmospheres of the Outer Planets”, 2002

Art by David Seal of JPL

Imagine an Interplanetary Future Where -

- d-He3 fusion produces most of Earth's energy needs without radioactivity or carbon emissions
- Space transportation has been revolutionized by an efficient fusion propulsion system with exhaust velocity up to 0.088 c
- Space commerce is stimulated by the existence of an interplanetary cargo worth $3-M a kilogram
- Unmanned probes travel to the nearest star systems with flight times less than a human lifetime

He-3 Fusion for Energy & Propulsion

<u>d + He3 --> p + He4</u>

- reactants are stable and storable
- products are energetic, charged and stable
  - Efficient electrical generation from MHD
  - No activation and embrittlement of reactor vessel
  - Efficient conversion to thrust with exhaust velocity up to 0.088 c --> ~50 yr interstellar flight using known physics.
- 3.6×10^{14} J/kg of d-He3 mixture = 1.0×10^{8} kWh/kg
  - Fuel is about 20% of the kWh cost of electricity
  - If electricity is 15¢/kWh then He3 has a value of <u>$3M/kg</u>

He-3 is one of the few commodities worth interplanetary freight costs

Why Outer Planets for He-3?

- Earth: breeding of tritium from either isotope of lithium by neutron bombardment, tritons decay to He-3.
  - Containment, waste problems same as d-t fission.
  - USA has no current capability.
  - Lithium inventory?
- Moon: solar wind implanted in regolith, 10 ppb (10^{-8}) by mass in uppermost few meters. ~1000 yr of 2001 energy needs- a starter catalyst?.
- Outer planets: primordial He3, ~10 parts per million (10^{-5}), ~10^{9} yr of 2001 energy needs- the ultimate energy source?.

Which Outer Planet-Jupiter

Pro:

- Closest to Earth and Sun

Con:

- Huge gravity means return vehicle has mass ratio >20 (nuclear thermal I_{sp} = 900 s)
  - No mass budget left for cargo!
- A lot hotter at a any given density
  - Galileo probe killed by heat not by pressure

Which Outer Planet-Saturn

Pro:

- Not as far as Uranus and Neptune
- Rapid rotation substantially reduces ΔV to orbit

Con:

- Seen as depleted ~5x in Helium compared to other outer planets
  - reanalysis of Voyager data 20 yr later restores that 5x- maybe
  - won’t know for sure until we send an entry probe
- Rings as a navigation hazard
  - need close-in, co-orbiting mission to look

Which Outer Planet-Uranus

Pro

- Primordial He3 abundance ?
- ΔV to orbit requires mass ratio < 5
- Closer than Neptune

Con

- Axial tilt complicates interplanetary travel
- Twice as far from Earth as Saturn

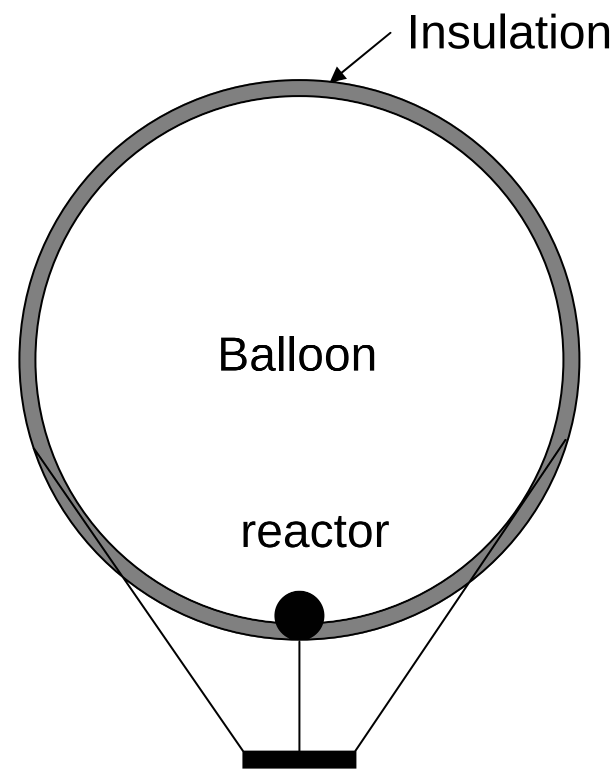
Uranus may be the closest planet without major possible problems -- but we must return to both Saturn to be sure

Do we really know how much He3 is there?

- He3/He4 cannot be measured by remote sensing
- He3/H_2 and He3/He4 ratios have been measured *in situ* only by *Galileo* at Jupiter
- He3/He4 ratio of 10^{-4} to 1.5×10^{-4} from meteors, solar wind, cosmology
- Use *Galileo* results for He3/He4 = 10^{-4} and Voyager results (?) for He4/H_2

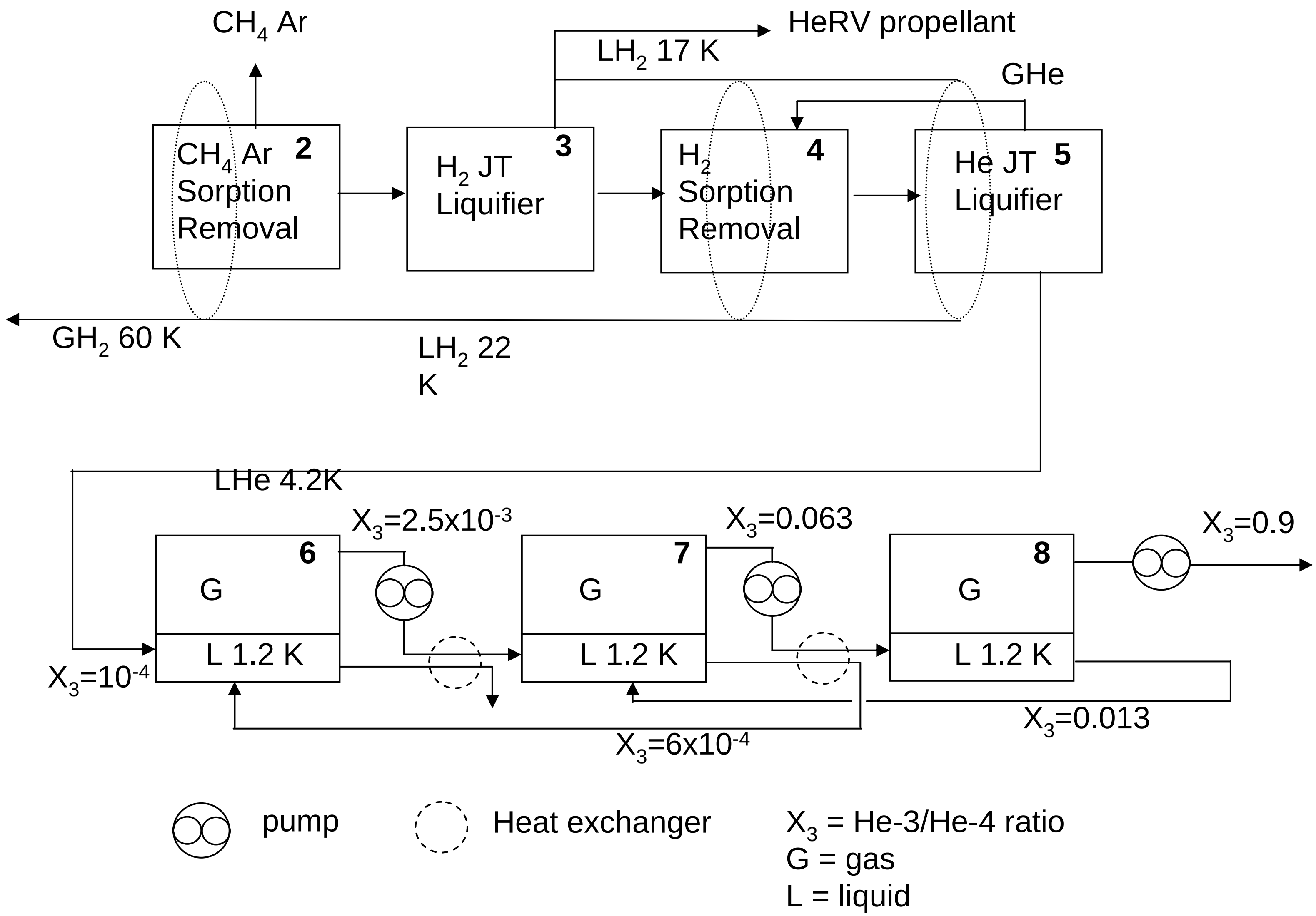
He-3 Mining with Balloons

- Balloon diameter : 80 m
- Total Plant mass: 146 tonnes
- Return vehicle: 59 tonnes
- Total lift needed: 205 tonnes



Notional Distillation Plant Concept

Thinking Big about our Space Cryogenics Future



Energy Economics

$He3/H_2 = 10$ ppm

Table 1

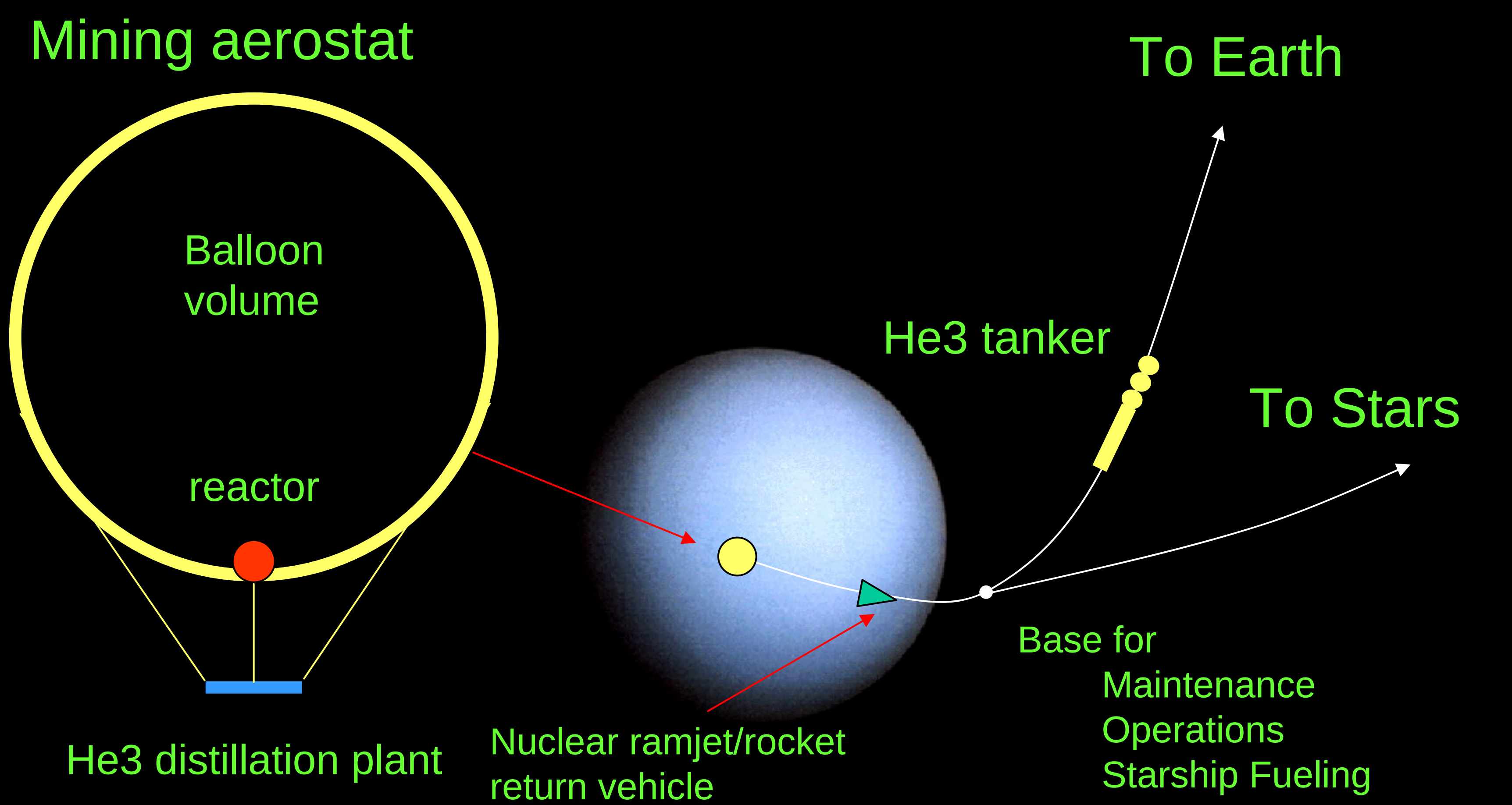
Stage	Process	Energy (J)/g He3
1, 2, 3	cool atmosphere to 16 K	$7.2x10^7$
3	liquify H_2 at 16 K	$3.2x10^8$
5	cool He from 16 K to 4.2 K	$1.3x10^7$
5	liquify He at 4.2 K	$1.1x10^7$
6	cool LHe from 4.2 to 1.2 K	$1.2x10^7$
total		$4.3x10^8$

Transportation on 2 yr trajectory: $5x10^7$J/g He3

Energy released: $6x10^{11}$ J/g He3

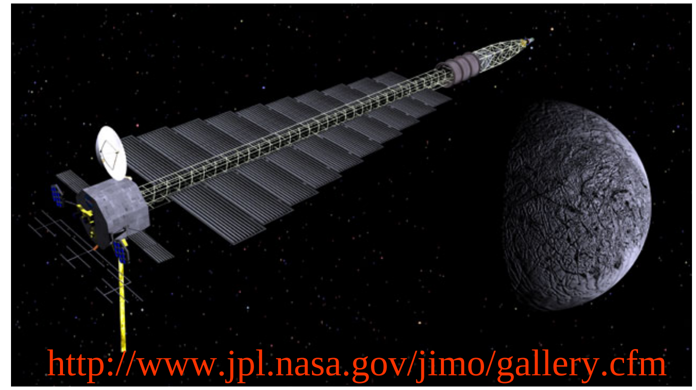
Theoretical energy payback: ~1000

The Persian Gulf of the Solar System, 2150



The most valuable interplanetary commodities are refined He-3, deuterium, and heavy metals

Next Steps



- Jupiter Icy Moons Orbiter (JIMO)
  - nuclear fission-powered
  - electric propulsion flight system
  - Big deal: 20 tonnes, >$4 B, 10 kWe
  - First of a series: Project Prometheus
- Saturn Ring Observer
- Uranus/Neptune Orbiter with Probes
- Self-deploying balloon probes for Mars, Titan
- Discovery/New Frontiers missions to other resource sites (Moon, asteroids, comets) for interplanetary commodity economy

A Trial Balloon ?

Scientific balloon missions to outer planets, using Pu RTGs and/or O_2 burners, to study

- He3/He4 and He/H_2 ratio
- pressure vs. temperature for $1 < p < 100$ bar
- trace gas composition
- entry, deployment, and telemetry engineering experiments

A science balloon could be as small as 2.8 m diameter, and use at most 7 kg of Plutonium as a heat and power source